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Combustion Gas Synthesizer-Phase II

COMBUSTION GAS SYNTHESIZER - PHASE II

Final Report

USDA Forest Service/University of Washington

Cooperative Agreement INT-90457-RJVA

August 16, 1990 through October 31, 1992

by

Richard C. Corlett
Principal Investigator

August 30, 1993

Scope and Organization

This report covers the most recent phase of a cooperative program between the USDA Forest Service and the University of Washington. The USDA Forest Service technical monitor was Dr. Darold E. Ward of the Missoula, Montana Fire Laboratory of the Intermountain Research Station. The University of Washington work was done within the Department of Mechanical Engineering, with Professor Richard C. Corlett serving as Principal Investigator. This program existed continuously from July 6, 1988 to December 31, 1992. It included Cooperative Agreements INT 88320 and INT-90457. This report covers the most recent Cooperative Agreement INT-90457-RJVA for the period August 16, 1990 through October 31, 1992.

A small fraction of the funds provided under this series of Cooperative Agreements was intended to support the direct collaboration of Professor Corlett with scientific personnel at the Missoula laboratory. However, nearly all of the resources went to work aimed at a practical development of a long residence time, fuel rich combustion gas synthesizer. Its purpose was to obtain, for an arbitrary pulverized biofuel, incomplete combustion products for conditions thought to be typical of large fires. The original interest was in fire phenomena postulated in nuclear winter scenarios. This was superseded by a more general interest in large area wildland fires as air pollution sources. The general plan was to couple the output of this synthesizer with a lean diffusive reactor, such as the University of Washington's 2.6 m^3 pressurizable fire chamber, to obtainable controllable laboratory characterization of gaseous and particulate pollutants as a function of bio-species and pertinent combustion variables.

Professor Corlett developed the gas synthesizer concept late in 1988 after discussions with USDA Forest Service personnel. This was analyzed and designed, and fabrication started, by a graduate student, Mr. Robert S. McKee. His work is described in a report, previously submitted to the sponsor and dated June 17, 1989. This work was taken over by another graduate student, Mr. Michael S. Tarner later in 1989. His assignment was to complete the development of the gas synthesizer. Tarner completed an M.S. Mechanical Engineering thesis, "Laboratory Simulation of the Effect of Long Residence Time on Soot Formation in Forest Fires," in the Summer of 1992. A report derived from this thesis is included here as Part I. It is noted that this USDA Forest Service-supported work by Mr. Tarner was only part of his assignment during the 1989 to 1992 pericd. About half of his support came from other contracts for different tasks which, however, also addressed smoke problems.

The work supported by these projects did not did not get nearly as far as had been hoped. Part II discusses the technical basis for this limited progress and makes recommendations for future research. The Principal Investigator will be pleased to travel to Missoula, Montana or other site to discuss these recommendations.

Part I

LABORATORY SIMULATION OF THE EFFECT OF LONG RESIDENCE TIME COMBUSTION ON SOOT FORMATION IN FOREST FIRES

University of Washington MS Mechanical Engineering Thesis

by

Michael S. Tarner

August 1992

Edited and condensed by

Richard C. Corlett
Principal Investigator

For inclusion in:

FINAL REPORT

USDA Forest Service/University of Washington

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Glossary

A	Area
AFR	Air to Fuel Ratio (lb/lb)
β	Buoyancy
C	Constant
F	Shape Factor
g	Acceleration of Gravity
Gr	Grashoff Number
h	Local Heat Transfer Coefficient
$H_{f_{298}}$	Enthalpy of Formation
ΔH_{sens}	Sensible Enthalpy
k	Thermal Conductivity
L	Characteristic Length
$\dot{m}$	Mass Flow Rate
η_i	Moles
Nu	Nusselt Number
P	Power
Pr	Prandtl Number
q	Heat transfer
Q	Volume Flow Rate
R	Thermal Resistance
Ra	Rayleigh Number
Re	Reynolds Number
t	Time
T_r	Residence Time
t_1	Interior Wall Temperature
t_2	Exterior Wall Temperature
t_{inside}	Interior Temperature
$t_{ambient}$	Environment Temperature
T	Torque
T_{exit}	Exit Temperature of Gases
u_∞	Free Stream Velocity
V	Volume
x	Distance
Δx	Wall Thickness
X	Mole Fraction
ε	Emissivity
λ	Wavelength
ρ	Density
ϕ	Equivalence Ratio
υ	Kinematic Viscosity
ω	Angular Velocity

Subscripts

bio	Biomass
C	Forced Convection
CH_4	Methane
e	Equivalent
$free$	Free Convection
k	Conductive
L	Characteristic Length
O_2	Oxygen
rad	Radiation
x	Characteristic Distance

Superscripts

m	Empirical Constant
P	Products
R	Reactants

Chapter 1

Background

1 Introduction

This report describes the design, development and preliminary operation of a burner intended to burn a variety of bio-fuels under fuel rich, long residence time conditions. Residence time is here defined as the mean time that reactant matter derived from fuel remains within the oxygen deficient reaction zone.

In the USA approximately 5 million acres annually are treated with prescribed fires (Peterson 1991). One benefit is reduction of accumulated biomass, which can result in high intensity uncontrollable fires releasing large amounts of atmospheric pollutants (Ward, et al. 1976). But controlled burning also can impact air quality. To be able to formulate optimal management strategies, the USDA Forest Service and other land management agencies need a better understanding of the emissions from both controlled and uncontrolled wildland fires. This includes quantification of amounts and air quality impacts of the spectrum of gases and particulates produced.

A principal concern is the effect of particulate matter on thermal radiative heat transfer through the atmosphere. Particle size is important. Factors thought to determine particle size in fire emissions include fuel composition and water content, fire intensity and residence time (Ward and Hardy 1991).

The independent role of residence time is unknown but may be important. Soot and other particles are formed in fuel rich combustion regions. It is physically reasonable that, as a fire intensifies, it produces a growing fuel rich volume with the stoichiometric mixing zone driven further from the gasifying fuel. It is hypothesized that this would lead to a greater mass particulate yield and larger particles. Information to test these hypotheses and quantify dependencies of mass yield and particle size on fire length scale and intensity does not now exist.

There are limited avenues for obtaining the desired information. Work with full-scale phenomena is expensive even on a run-by-run basis. The amount of replication that would be required to compensate for the effect of random environmental variables such as wind and humidity would bring the cost to totally unacceptable levels. On the other hand, we have to preserve the characteristic times and energy levels of the phenomena of interest.

In this research, an experimental concept is adopted which abandons some of the features of a free-burning fire but does offer complete experimental control, at least from the standpoint of replication, and obtains residence time and equivalence ration values thought to typify the fuel-rich zones of large wildland fires. In essence, the experiment consists of a large stirred reactor. Stirring is accomplished by the injected stream of air and possibly other gases. The fuel is pulverized biomass which is entrained by one of the inlet gas streams. In principal, this last feature allows the study of any type of bio-fuels.

Preliminary development of this concept was carried out by Robert McKee. A prototype conical-shaped chamber is depicted in Figure 1.1. The key design parameters are residence time t_r up to 10 sec and (fuel-rich) equivalence ratio ϕ = 1.4 based on suggestions by

Wright (1969), Glassman (1987) and others that the $\phi = 1.4$ is the critical smoke point for most gaseous fuels. Nominal maximum fuel particle size was 2 mm. This development has been reported by McKee (1989).

The objectives of the research reported here were to complete the development of the gas generator, to demonstrate its performance and to proceed with measurements of the effects of long fuel-rich residence time on gases and particulate matter produced by the system. As it turned out time and resources did not permit work beyond the performance demonstration phase.

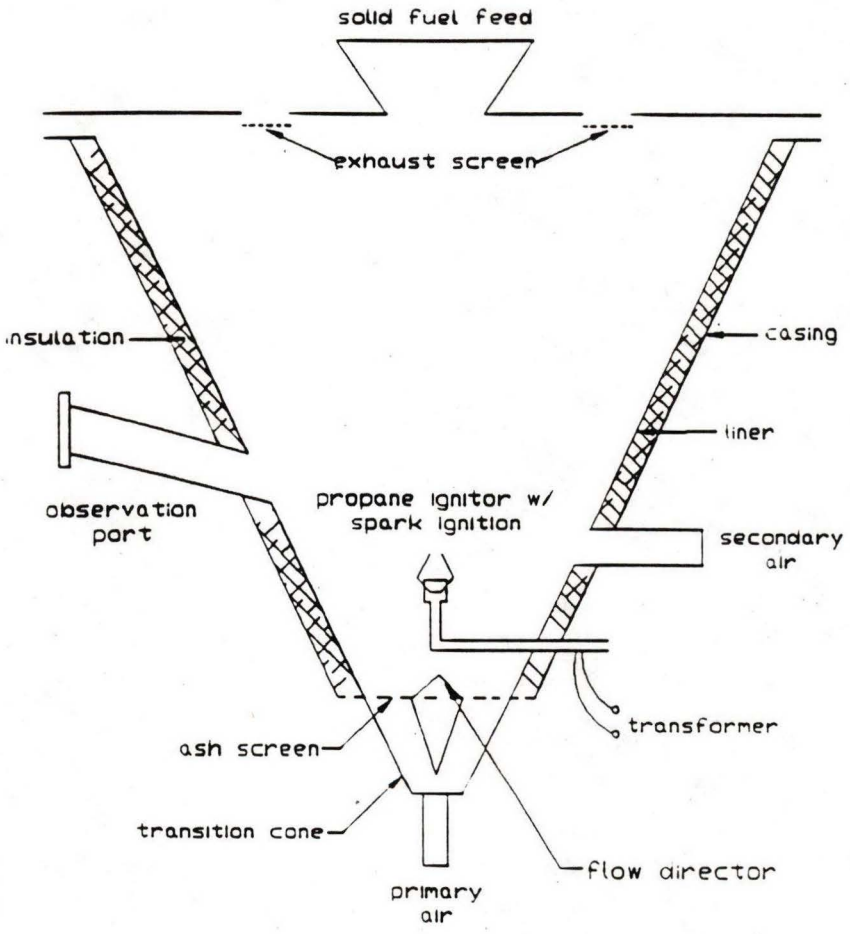

Figure 1.1 Prototype Design

Chapter 2

System Description

2.1 Introduction

This chapter describes the combustion system and its major components. The burner is depicted in Fig 2.1. Pulverized biomass fuel, metered by an auger, is fed into an eductor. Combustion air passes through the eductor entraining the biomass creating a quasi-premixed fuel. This mixture flows to the reactor where it is entrained into a circulating flow pattern and is burned in the presence of a methane pilot flame. The gases produced therefrom, are then sampled and analyzed.

2.2 System Design

The experimental apparatus is depicted in Fig. 2.1. It consists of four distinct assemblies; furnace, burner, feeder, and instrumentation. The apparatus is supported by a frame constructed of nominally 2.54cm x 2.54cm (1" x 1") square steel tubing.

2.2.1 Reactor Assembly

The reactor as depicted in Fig. 2.2 has a volume of 0.26 cubic meters and consists of several major elements. The first subsystem is the conical section listed as the transition zone. It is flanged to the liner to allow easy access to the bottom of the cone. Here the primary combustion air enters and is directed along the sides of the chamber by the flow director, thus producing a recirculating pattern inside the chamber. In addition to directing the air along the furnace wall, the flow director also controls the velocity at which the air enters the chamber. This allows for reduced volumetric air flow, while maintaining the minimum suspension velocity. The transition cone also serves as the anchoring point for the burner.

The next element is the combustion zone. Here, the premixed fuel is burned in a fuel-rich mixture. The reaction is contained by the furnace walls, which consist of an outer shell and an inner liner separated by a 2.5cm blanket of Kaowool 6LB density ceramic insulation. The outer casing is constructed of 16 gauge mild carbon steel and the liner is constructed of 20 gauge mild carbon steel. The liner is removable to allow it to be weighed before and after testing to determine the amount of condensed pyrolysates and carbonaceous sold is present.

The lid comprises the last element. Constructed similarly to the chamber walls with two layers of metal separated by insulation, it has four symmetric 5cm diameter holes to allow exhaust removal and gas sampling. The upper cover, constructed of 16 gauge mild carbon steel, is attached to the lower cover by two angle pieces of steel welded to both to provide rigidity. The lid is attached to both the frame by eight 1.27cm (0.5") diameter bolts and to the outer casing by twenty-four 1.27cm (0.5") diameter bolts.

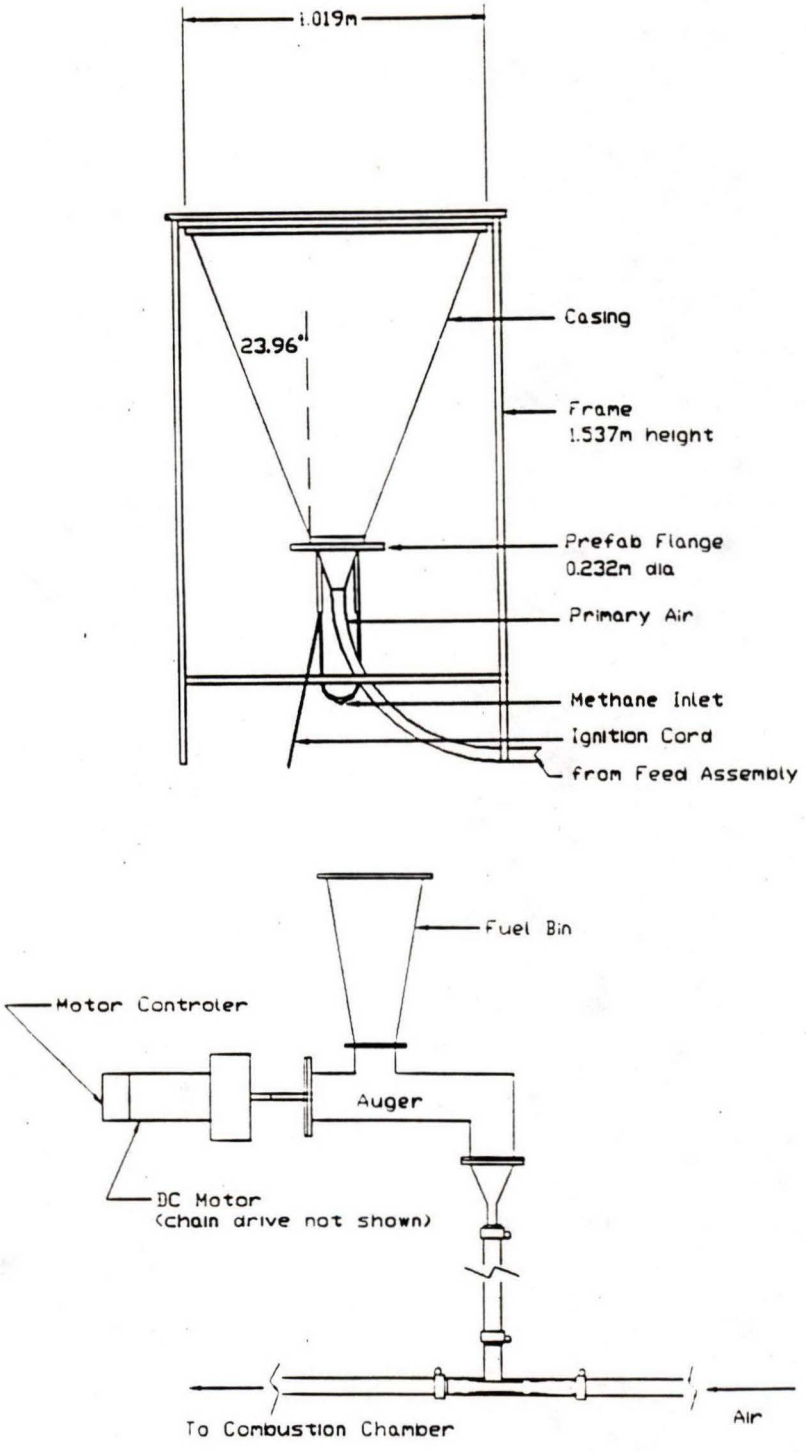

Figure 2.1 System Design

2.2.2 Burner Assembly

The burner assembly as depicted in Fig. 2.3 provides a continuous source of energy to the combustion zone to maintain combustion. It passes through and is anchored to the transition cone using hose clamps as depicted in Fig. 2.2. It is constructed from 0.64cm (0.25") steel tubing bent into a 7.62cm (3") diameter circle to provide an even flame surface. The burner surface contains twelve 0.236cm diameter holes. Attached to the top of the burner is a mesh screen, which provides an attachment point for the flame in the air stream. The burner supports were made from 1.27cm (0.5") steel tubing. The supports allow the burner to be adjusted from 2.5cm to 30.5cm above the flow director. The methane gas flows to the burner through 0.64cm (0.25") tubing located within the supports. In addition, there is space available inside to insert probes or thermocouples into the chamber. The methane gas system pressure is controlled by an Air Products E11-N515D single stage regulator at the bottle. The methane flow rate is metered by a Cole Parmer L-03292-18 4SCFM flow meter.

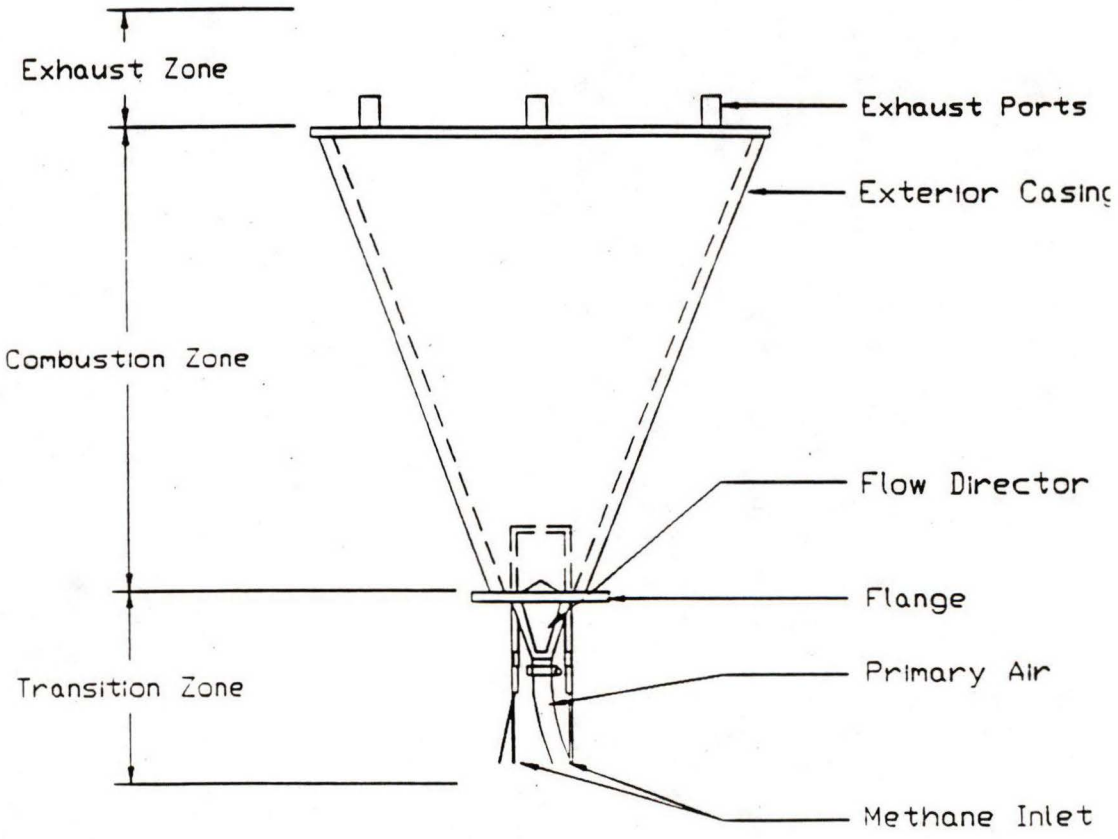

Figure 2.2 Furnace Assembly

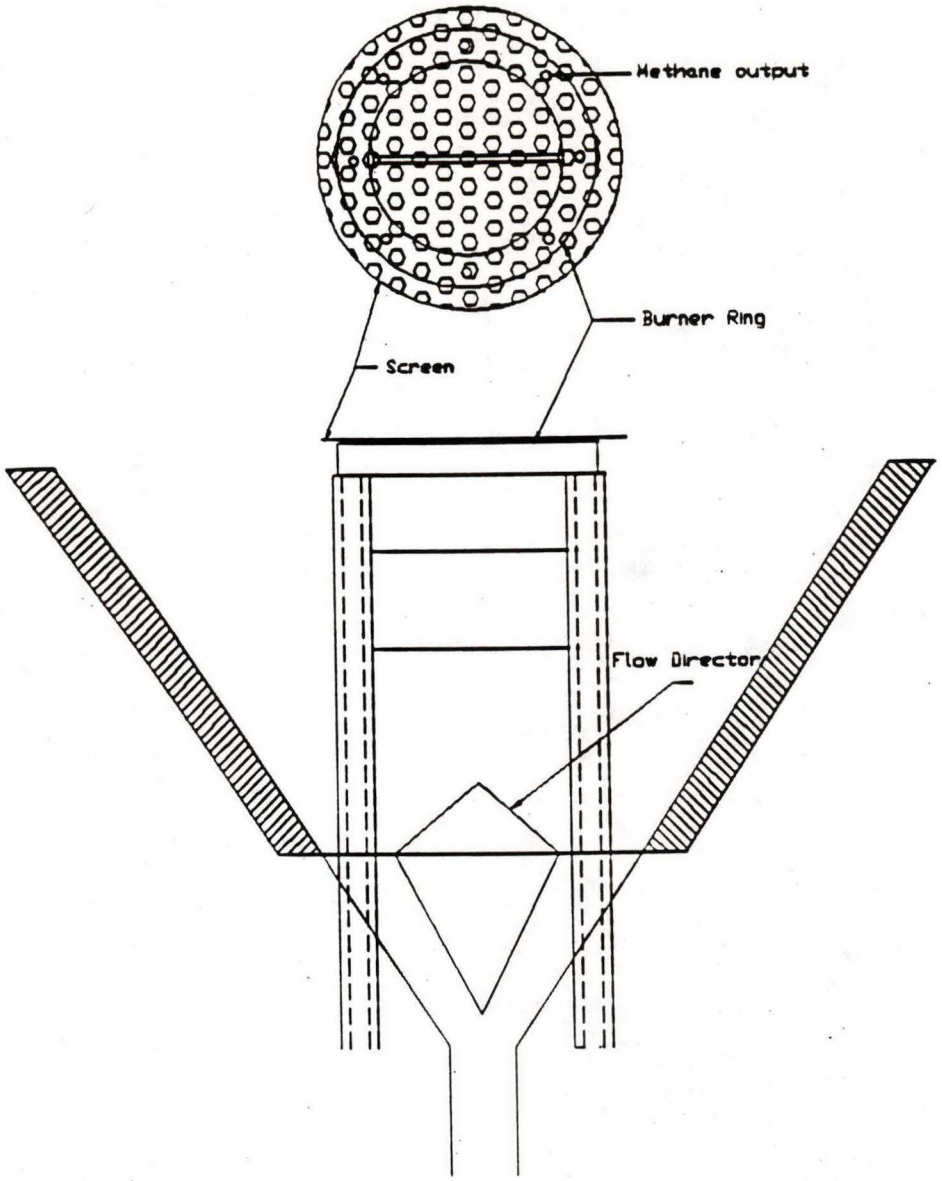

Figure 2.3 Burner Assembly

2.2.3 Feeder Assembly

The feeder assembly as depicted in Fib. 2.4 provides a controlled feed rate of pulverized biomass fuels to the combustion chamber. The fuel is placed into a 0.04m^3 head tank and gravity fed into an auger, which is driven by a 90 volt 25 watt Dayton DC motor and controller. The auger and motor control the input feed rate and provide biomass fuel from 0.245 g/s to 2.362 g/s. The motor's input electrical voltage is reduced by a variance from 120 volts to 90 volts. The signal is then converted to DC by a full wave rectifier. Next the biomass is injected into the chamber through the use of an in line eductor. The eductor, as depicted in Fib. 2.5, is a 1.91 cm (3/4") series 300 SCE- cs Solids Conveying Eductor manufactured by Fox Valves. It provides a solids conveying rate up to 7.6 g/s. The primary combustion air passes from a 1.91 cm (0.75") hose to a 0.64cm

(0.25") opening at the eductor. This creates a suction at point A, where the biomass is introduced from the auger. The air and biomass mix then proceed through a 1.91cm (0.75") hose to the chamber. The feed assembly allows for biomass premixed equivalence ratios from 0 to 3.

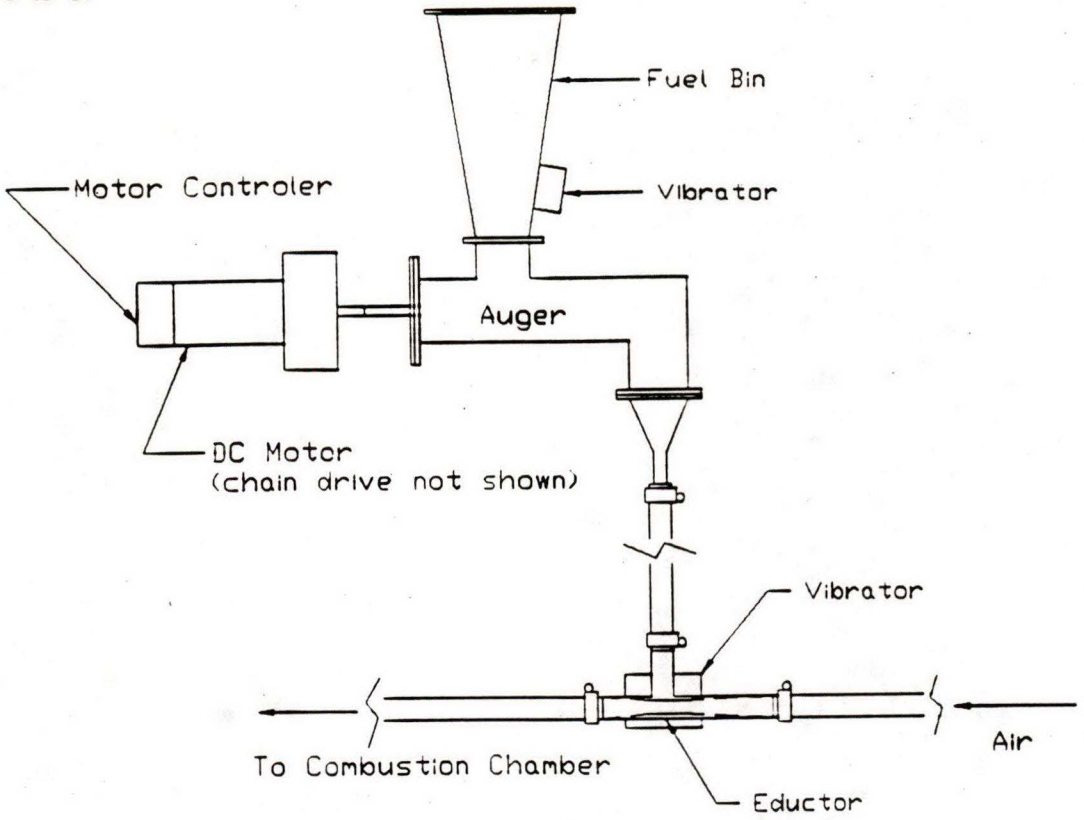

Figure 2.4 Feeder Assembly

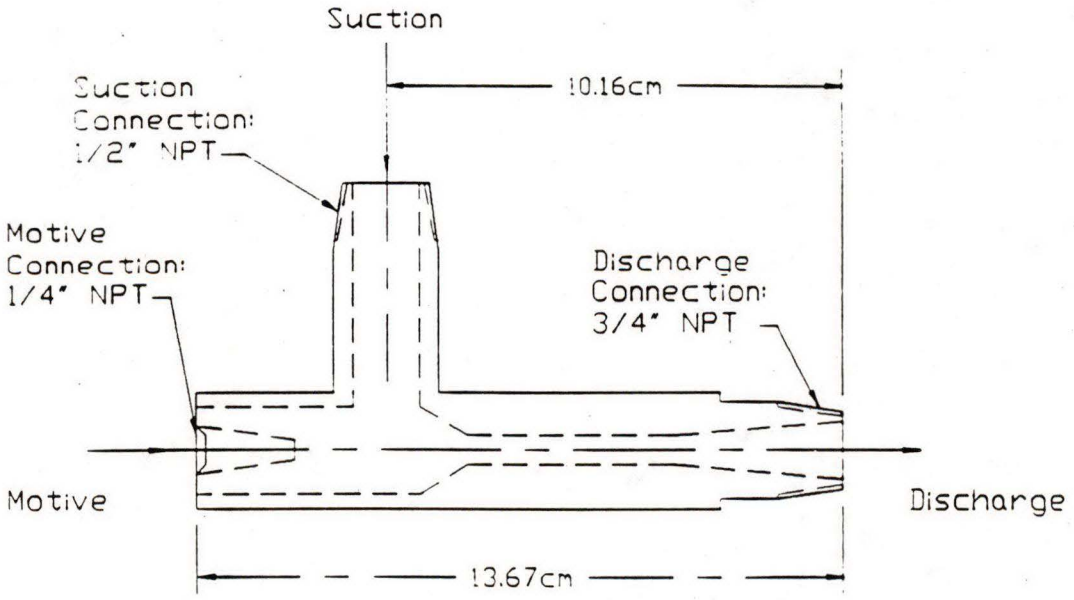

Figure 2.5 Eductor

2.2.4 Instrumentation

The primary combustion air flow rate, plant air provided at a pressure of 689.5kPa, was measured by a Cole Parmer I-03269-34 Variable Area Flow meter prior to entering the eductor.

All temperature measurements were taken using 30 gauge type K thermocouple wire manufactured by Omega. They were recorded by hand, using a 2100A Digital Thermometer manufactured by the John Fluke Mfg. Co.

The exit gases were sampled by extracting the gases with a General Electric 75 Watt (0.1 Hp) pump. The gases, after passing through a cold trap, were then sampled using a Servomex series 1400 CO_2 and a Servomex Series 572 O_2 analyzers.

Chapter 3

Developmental Experimentation

3.1 Introduction

The objective of this investigation was to design a long residence time, fuel rich combustion chamber in order to characterize particulate emissions from this type of fire. In what follows, the equivalence ration ϕ is expressed on a fuel-rich basis ($\phi > 1$ implies a fuel-rich mixture). This chapter discusses the experimental and investigative work required to obtain the reactor depicted in Fig. 2.1 from that originally proposed in Fig. 1.1. Testing began by cold flow experiments on the full scale reactor reported by McKee (1989). After fabrication and bench scale testing of the burner, a hot flow experiment was conducted to verify an even temperature distribution inside the reactor. Upon completion of these preliminary tests, final testing began by trying to achieve a fuel rich equivalence ratio using methane only. Once this was accomplished testing continued with trying to obtain a fuel rich equivalence ration using a methane-biomass flow.

3.2 Component Tests

Upon completion of initial construction of the reactor, the first step was to verify that the chamber had the same cold flow characteristics as the prototype. Again, mock fuels, such as packing material and sawdust, were used to examine the effects of entrainment and backmixing. After visual confirmation of cold flow patters, the design proceeded on the pilot burner. The original design had a fixed line burner as the source flame, but since the exact flow patter, created by heat addition, could not be determined, the ability to vary the flame's position provided the flexibility needed to ensure optimal flame placement for good mixing. The burner needed to provide sufficient energy to initiate combustion, to sustain combustion, and to provide even heating inside the chamber. Bench tests were conducted, utilizing line burners. to determine hole size and spacing needed to achieve an even flame spread. In order to provide symmetrical energy addition and minimize the interruptions to the air flow, a circular diffusive burner, as depicted in Fib. 2.3, was chosen. After installation of the burner, tests were conducted to determine the temperature profile inside the chamber. It was imperative that the flame provide even heating within the chamber. An even temperature distribution demonstrates sufficient and complete mixing. Seven thermocouples were placed at a variety of locations to verify the temperature distribution:

1) one at each exhaust port. (#4, #6)
2) one at 0.3 meters below the lid at each exhaust port. (#3, #5)
3) one at 0.3 meters above the burner. (#7)
4) one at the burner level. (#1)
5) one at 0.3 meters below the burner. (#2)

With the thermocouples positioned temperature mapping began. The flowmeter used for these tests was a Cole Parmer FM 044-40ST with a linear scale reading from 0-150. A copy of the flowmeter calibration data is included in Appendix A. The temperature data was collected by a Metrabyte EXP-16 Multiplexing Board connected to a DAS-16 Board A-D converter, installed inside a Zenith 386 25 MHz computer. The data acquisition program is Labtech Notebook. All of the graphs were done by Lotus 123. The burner was positioned at three different heights above the flow director 2.5 cm, 15.5 cm, and 30.5 cm. At each one

of these positions, the methane flow rate was varied from 13,048.5 ml/min to 50,000.0 ml/min. At each methane flow rate, a temperature profile was mapped for each of three different air flow rates, 1.1m³/min, 1.6m³/min, and 2.3m³/min. These three flow rates were selected because, as discussed in the next section, they bracket the calculated flow rate. The temperature profile shown in Fig. 3.1, illustrated the even temperature distribution inside the chamber. The upper line in the graph is thermocouple 1 located in the flame. In the process of conducting these tests, it was observed that the combination of flame height methane flow and air flow caused a variation in flame stability. The position that provided the best flame stability occurred at 15.5cm.

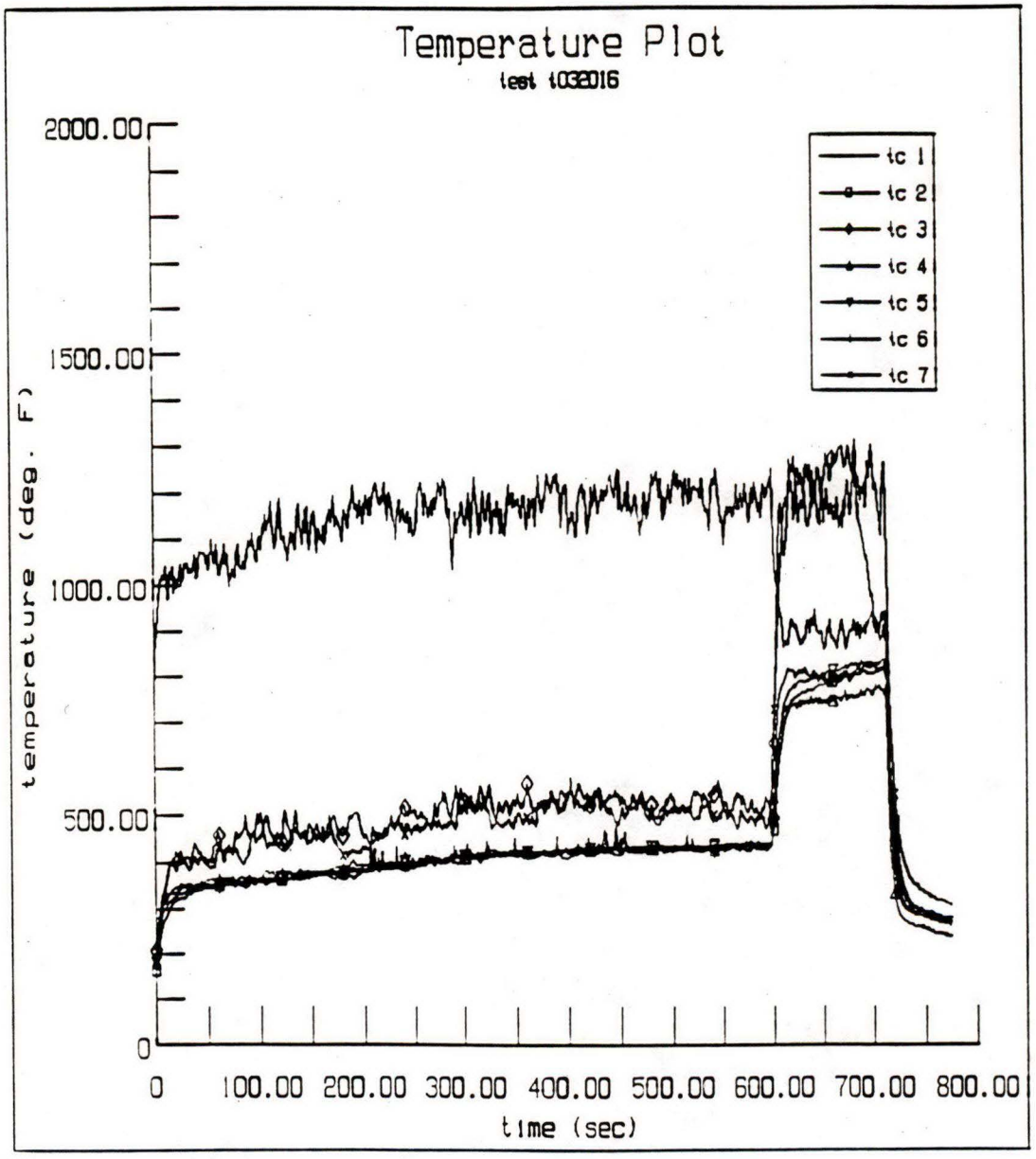

Figure 3.1 Temperature Profile

3.3 Design Testing

Upon completion of the temperature mapping, measurements were conducted to determine the equivalence ration inside the chamber prior to the addition of biomass. The goal of these first tests was to obtain a fuel rich mixture prior to adding biomass. Therefore, the addition of biomass increases the equivalence ration, producing a more pronounced fuel rich condition. The preliminary modeling was based on a desired residence time of 10 seconds. Therefore, the volume flow rate of air needed was:

$$Q_{air} = V/t$$

Based on this equation, the standard air flow rate needed was calculated to be 1.6m³/min. To initiate testing, the burner height was set at 15.5cm, the air flow at 0.28m³/min, and the methane flow at 13,050ml/min (flowmeter scale of 40). Thermocouples were placed at each of the exhaust ports in the lid. After the mixture was ignited, the air flow was increased to 1.6m³/min. Once the chamber reached a steady state, temperatures and flow rates were recorded by hand. The methane flow rate was then varied in increments of 10, until flame extinguishment at a setting of 50,000ml/min (flowmeter scale of 130). This produced equivalence ratios from 0.13 to 0.5. Increasing the methane flow rate beyond this point caused the pilot flame to extinguish. The burner height was then varied to determine if this was still the optimal position of the burner. Raising and lowering the burner reduced the maximum methane flow rates of extinction. At low methane flow rates, it was observed that the flame began several centimeters above the burner. As the flow rate increased, this separation became greater. At the higher methane levels the flame became unstable, dancing from one hole to the next. Based on these observations, it was determined that turbulent mixing at the burner surface caused flame extinction. This problem can be eliminated in three ways:

1) enlarge the burner holes.
2) manufacture flame attachments.
3) add a non reactive gas.

Altering the burner permanently, such as increasing hole size, should be used as a last resort, because this would alter the established operating parameters. Adding flame attachments reduced the flow velocity of methane and increased flame stability. The addition of a non-reactive gas assists in flame stability, as it displaces part of the oxygen in the combustion air. Therefore, less methane is needed for a given equivalence ratio.

Initial attempts at flame stabilization centered on providing a flame attachment. A plethora of devices, including wire and mesh screens laid over the holes, was tried. None allowed for equivalence ratios much greater than those already established. Up to this point, the highest recorded temperatures were 500° C at the exhaust ports and 800° C directly over the burner. This latter temperature, measured at an equivalence ratio of 0.5, was 400° C below that calculated by the equilibrium program. (As discussed later, the actual equivalence ratio was 0.3, therefore these temperatures correlate more closely). It was still a major concern, that a possible large scale deformation might occur if the chamber were allowed to burn at $\phi = 1$. Steffensen et al (1966) lists the adiabatic flame temperature of methane at 2223° K, which is 700° C above the melting point of the steel used in construction.

3.3.1 Burner Modification

With this in mind, and the inability to stabilize the flame with a flame attachment, the next step was to introduce a non reactive gas into the chamber. Nitrogen was the obvious choice, due to the fact that it is relatively inexpensive, common and already a major constituent of air. The addition of nitrogen into the primary combustion air helped in several ways. First, it increased the equivalence ratio by reducing the amount of available oxidizer. Secondly, an overall reduction in temperature occurs because more energy is needed to heat up the N_2. Initially, the nitrogen was placed into a 0.74m³ tank at a pressure of 3.10 MPa. The nitrogen passed from the tank through a globe valve, which regulated the flow into a Y fitting mixing with the air. This mixture then passed through a rotometer and into the chamber. The burner was lit, as discussed previously. The air was then increased to 0.34³/min. Once the system stabilized, the nitrogen was turned on. These initial tests proved to be too short to obtain any relevant information. As soon as the nitrogen was added, the flame went out. Any changes in burner height did not ameliorate this condition. It was thought that the relative instability of the flame, combined with addition of nitrogen, caused the local burner mixture to be too fuel rich to support combustion. In addition, the temperatures measured when the burner remained lit were much too low to be of any use. In order to simulate temperatures measured in forest fires, the temperatures had to be between 800°C and 1000°C. In order to overcome this mixing problem, it was decided to use a premixed methane / oxygen flame. While this exacerbates the equivalence ratio, a premixed flame guaranteed a stable flame at the burner. It was hoped that a reduction in the equivalence ratio would be offset by the controlled addition of nitrogen. In order to achieve this premixed state, a Victor type 315C welding handle was added up stream of the burner. A modified victor 3 type 4 welding tip provided complete mixing of the gases. Initial attempts to use a methane/air mixture failed, therefore, an oxygen mixture was used. compressed oxygen passed through a Victor regulator into a Cole Parmer flowmeter before entering the welding handle. Here the methane and oxygen mixed prior to enter the chamber. Testing resumed by verifying flame stability for different flow rates. Temperatures of up to 800°C were recorded for the runs without the addition of nitrogen.

3.3.2 Flow Modification

After reconfiguring the burner, the nitrogen tests were repeated. Since the flame was now independent of the surrounding atmosphere, this allowed for a more complete run. Observation of these runs demonstrated the inadequacy of this approach. The flow of nitrogen needed to maintain the residence time was too high for a prolonged run. This allowed only seconds of run time which was not enough to collect meaningful data. The pressure constraints of the tank and the relatively high pressure of the air contributed to these short runs.

In order to overcome these constraints, the nitrogen was injected directly form the nitrogen cylinder into the Y fitting. This corrected the pressure difficulties, as the pressure could be controlled more efficiently at the cylinder's regulator. It also allowed for longer runs, because the volume of gas contained in the cylinder was much larger than that in the tank. One problem with this method, though, was that the flow rates of nitrogen delivered were not high enough to assist in particle suspension. In addition, temperatures proved to be too low to adequately model the fire zones of interest. An important concern at this point was for runs in the absence of added nitrogen that the measured temperatures and those predicted by Steffensen did not correlate for a given ϕ.

Preliminary heat transfer calculations demonstrated that the heat loss from the chamber was not enough to account for the temperature differences.

After flowmeter recalibration, the previous premixed and diffusive tests were rerun. The results demonstrated that equivalence ratios were much lower than previously calculated. The maximum ϕ for premixed flames was 0.1 and for diffusive flames 0.3. This confirmed earlier suspicions that the chamber was too fuel lean and that another approach was needed. After reviewing the calculations, it was determined that variations in density were not being taken into consideration in the residence time calculations. Taking these variations into account, the actual residence times were less than one second. In order to achieve a residence time of ten seconds, the air input needed to be reduced considerably.

The next step was to determine if the chamber would operate in a fuel rich environment. The methane fuel rate was fixed at 26,000ml/min (flowmeter scale of 75) and the air flow varied from 0.1m^3/min to 0.68m^3/min, producing equivalence ratios from 3.69 to 0.59. The flowrate was incremented in steps of 5. At each increment, the air flow was varied from 0.42m^3/min to 0.85m^3/min. The maximum methane flowrate occurred at 32,840ml/min (flowmeter scale of 90), producing a ϕ between 1.13 and 0.58. Biomass experimentation demonstrated that 0.68m^3/min was the minimum air flow rate needed for particulate suspension and backmixing. At these flow rates, the maximum equivalence ratio was 0.87. In order to achieve a fuel rich mixture without altering the burner, it was decided to add biomass.

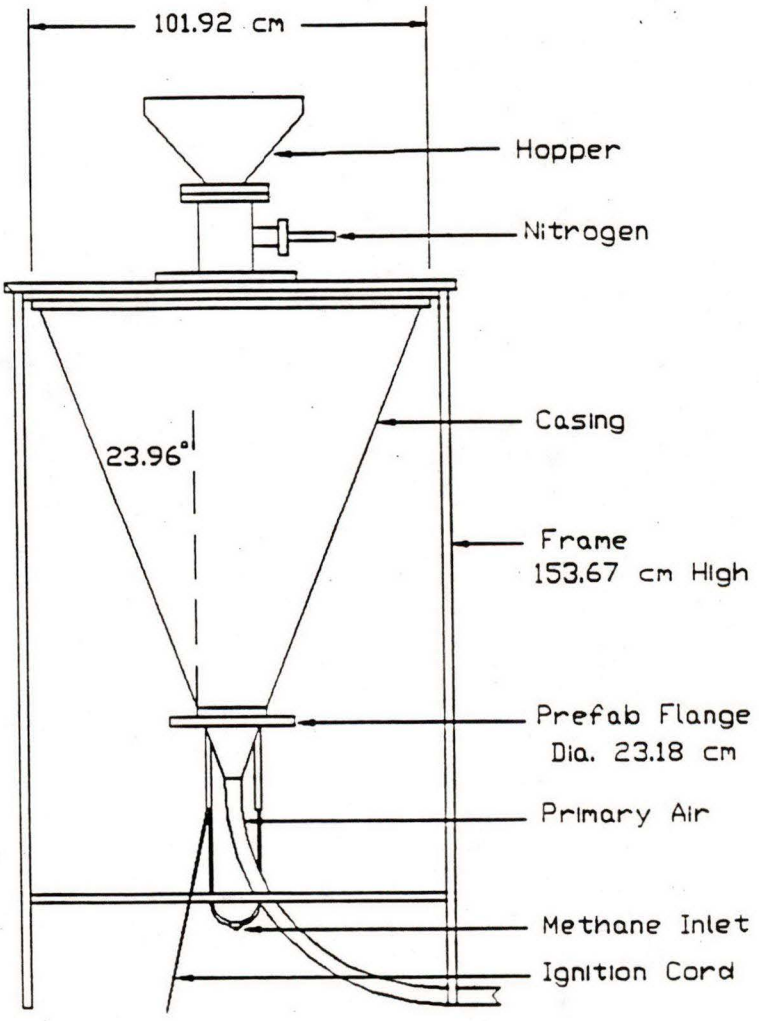

Figure 3.2 Original System

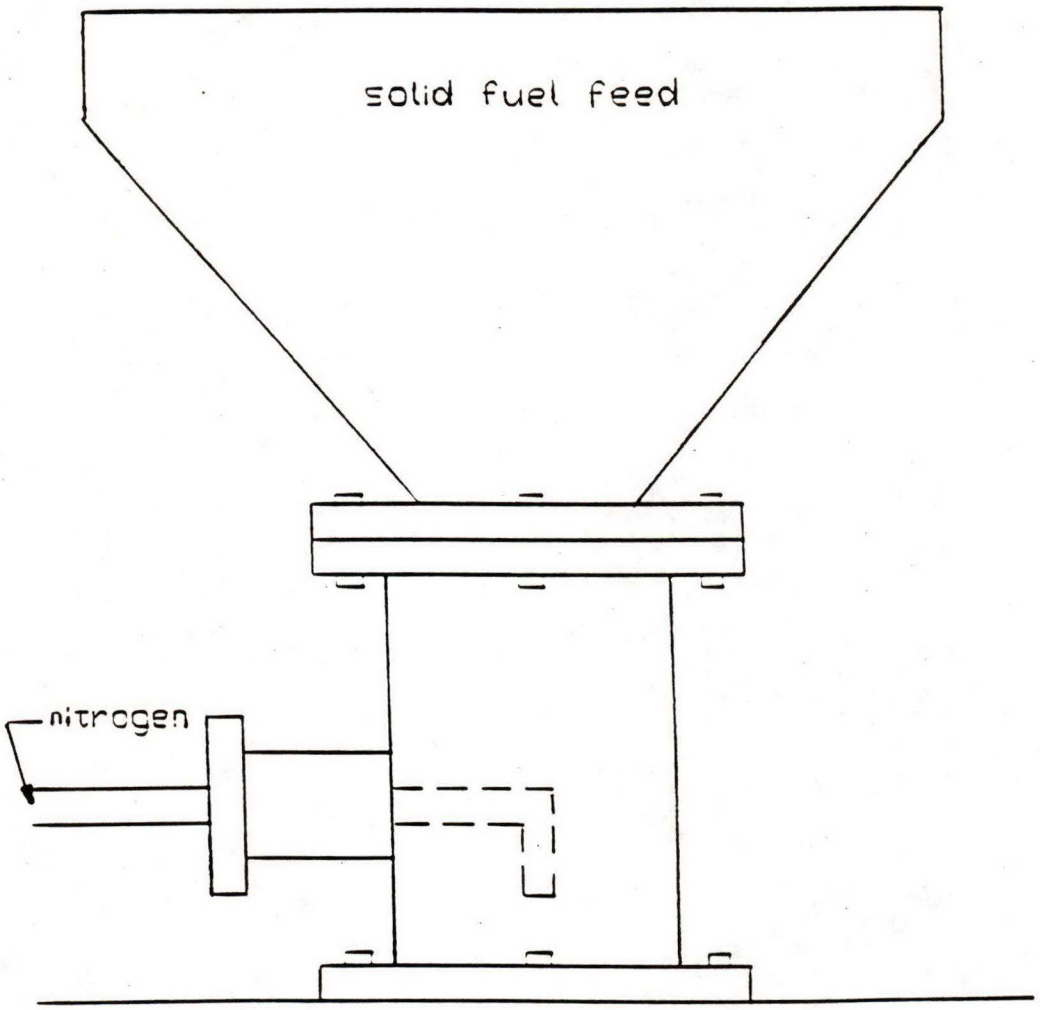

Figure 3.3 Nitrogen Feed

3.3.3 Feed Modification

The original design utilized a gravity feed system centered on the lid as depicted in Fig. 3.2. An Accurate series 300 feeder provided precision feed control at a rate of 2831 to 42475 cm^3/min. The biomass, placed into the Accurate, was augered into a hopper attached to the lid and then gravity fed into the chamber, under a slight positive pressure, expelled a portion of the biomass back out of the hopper, creating inconsistent feed rates. In order to prevent this, a cylinder containing a nozzle was manufactured and inserted between the hopper and the lid as depicted in Fig. 3.3. Calculations demonstrated that injecting nitrogen at this point would overcome the pressure allowing insertion of the biomass. One danger in this method, was the reduction in the overall equivalence ratio caused by the induction of unwanted air. Experimentation demonstrated that this configuration proved unworkable, as biomass continued to be ejected upward. Attempts to increase the nitrogen flow caused the flame to extinguish and reduced interior temperatures to levels unacceptable for modeling. In an attempt to prevent these

problems, it was decided to enclose the system. This was attempted by connecting a pipe from the reactor's lid to the Accurate's auger. The Accurate feeder was then sealed by placing a gasket on the lid with weights to secure it in place. It was hoped that by enclosing the feed system, this would create a backpressure which would assist in overcoming the interior chamber pressure. This approach suffered from many difficulties. First, the system could never be sealed properly to create a back pressure. As a result, bridging occurred inside the pipe preventing flow from entering at higher mass flow rates. At the lower mass flow rates, (those which did not produce $\phi > 1$) the flame moved toward the feeder causing an unwanted heating of the feeder.

The first series of experiments demonstrated that lower flow rates were needed to achieve the desired residence times, that higher methane flow rates were needed to achieve an equivalence ratio of 1.4, and that the biomass feed system needed to be redesigned. These experiments also demonstrated that the flame behavior was more stable at lower flow rates. The recorded temperatures, although higher with the addition of biomass, were still much lower than those predicted by the equilibrium program. A detailed heat balance was conducted to verify the heat loss. There were three thermocouples placed at the base, midpoint, and top of the chamber wall. On the lid, there were thermocouples placed at each exhaust, at the feeder entrance, and at two other random points on the lid. The chamber was allowed to reach steady state before temperatures were recorded.

Calculations (Appendix B) demonstrated that a substantial heat loss occurred through the lid, therefore the lid was redesigned as discussed in section 2.5.1. This redesign immediately increased temperatures 300^{o} C. With all of the variables explicitly identified, testing of the final design proceeded.

The first priority was to verify mathematically the data obtained experimentally. In order to accomplish this, the air flow rate of minimum particulate suspension was determined by drag force calculations. A standard spherical particulate size diameter of 2mm was assumed. for yellow pine, the calculations confirmed a minimum suspension volume flow of 0.68 m^3/min. Based on this flow rate, the maximum residence time for cold flow was established at 25 seconds. The equation for the residence time was:

$$t_r = V\rho/m$$

As the gas temperature increases from 25^{o} C to 1000^{o} C, the density decreases by a factor of 1/4. This produces a corresponding drop in the residence time to 8 seconds.

With the residence time firmly established, the next priority was to obtain an equivalence ratio of 1.4 using methane only. although air flow rates were lower, some difficulties still existed in maintaining a stable flame as the methane flow was increased. In order to overcome this, the hole size in the burner was increased to 2.4mm. In addition, a small screen was placed over the burner to aid in flame stabilization. After these modifications, exit temperatures increased to 800^{o} C and an equivalence ratio of up to 2.5 was recorded.

3.4 Final System Design

With the ability to maintain positive control over both the residence time and the equivalence ratio, the next step was to provide a reliable system for biomass addition. In redesigning the system, it was decided to create a premixed fuel by injecting biomass

upstream of the chamber. A tee fitting was inserted into the line. connected to the tee's stem was an air hose which in turn was attached to the Accurate feeder. the biomass was then fed into the hose and dropped by gravity into the tee. Pressure at the tee mouth caused bridging of the biomass blocking the feed. Again, an attempt was made to seal the system. A rubber gasket was installed on the Accurate lid and weights placed on top into the line. As discussed previously, bridging continued to occur because the system could not be sealed properly.

In order to insert the feed into the air line, a vacuum would need to be induced at the biomass feed inlet. One way to accomplish this was through the use of an eductor. An eductor, depicted in Fig. 2.5, uses a motive fluid such as air, to create a suction at point A. As the air flow enters the eductor, it is restricted creating a jet. Asthe air passes out the nozzle it creates an area of low pressure at point A, entraining the biomass. the premixed fuel is discharged at point C. The feed system was designed for a normal operating ϕ = 2,0 and a maximum biomass volumetric flow of 31.5 cm^3/s. This ensured that the input biomass would be in the fuel rich zone if and when sustained combustion was achieved. With these constraints established, a drivemotor and controller needed to be selected to operate the auger. Motor selection was based on the system starting torque and the required power. The starting torque was determined by attaching a spring scale to a gear of known radius on the auger shaft. The spring scale was pulled, until the fully loaded shaft began to rotate. The required force was recorded as the starting force and converted to torque. This was repeated ten times, to determine an average starting torque of 1.8Nm. The maximum required power for motor selection was determined by multiplying the torque (T) by the angular velocity (ω). The angular velocity required was based on the maximum feed rate, divided by the approximate volume moved by the auger per revolution. Based on the auger's size, the aproximate volume moved per revolution was 262.19 cm^3/rev. The maximum feed rate was 31.5cm^3/sec, therefore the angular velocity was:

$$\omega = V_{auger}/Q_{feed} = 0.12 \text{ rev/s}$$

The required power was then:

$$P = T\,\omega = 25W$$

A 90-volt DC Dayton motor fulfilled these requirements. Its selection required the design and fabrication of a full-wave rectifier and the installation of a variac for voltage control.

Upon completion of installation, testing commenced with the calibration of the new biomass feeder system. The biomass was placed into a hopper above the auger as in Fig. 2.4. A vibrator attached to the hopper's side prevented bridging of the biomass. The auger was then run for fourminutes at a controller setting of one. The biomass was collected and weighed to determine the mass flow rate. this was repeated three times at each controller setting of 1 - 10 to ensure consistency.

The addition of the eductor, while solving the feed problem, altered the air flow through the rotometer by creating a pressure drop across the rotometer. This required meter recalibration. The meter was recalibrated by adding a flowmeter downstream of the eductor and measuring the flow passing that point at standard conditions. To ensure that all air sources were being measured, a rotometer was connected to the suction side

of the eductor to measure the maximum air flow being drawn in. With calibration completed, the chamber was now ready for testing.

Chapter 4

Results

4.1 Introduction

The ultimate goal of this research is the ability to characterize the potential for particulate matter formation from different burned bio-fuels under fuel rich, long residence time conditions. To make the needed measurements, a specialized combustion chamber was developed (described in Chapter 3). In this chapter, results are presented which indicate the extent to which the design meets the objectives.

4.2 Test Results

The test procedure, as discussed in Appendix C, was developed early in the experimentation program. These procedures provided a standardized method for conducting tests. Deviations in the human response were minimized using standard operating procedures.

In the first series of tests, the objective was to verify, using methane only, the ability to positively control the equivalence ratio. In view of these goals, lower air flow rates than those used in subsequent test, were used to maintain the flame's stability. The results are listed in Table 4.1.

Table 4.1 Equivalence Ratio Verification

Q_{CH_4} $\left(\frac{cm^3}{s}\right)$	Q_{air} $\left(\frac{cm^3}{s}\right)$	$\dot{m}_{bio}$ $\left(\frac{g}{s}\right)$	ϕ	T_{exit} (K)	X_{CO_2}	X_{O_2}	t_r (s)
330	4500	0	.69	740	6.7	13.3	23
410	4500	0	.87	720	7.9	11.9	23
330	3800	0	.82	600	4.5	13.6	33
490	3800	0	1.23	740	7.5	9.3	27
570	3800	0	1.43	780	8.8	8.8	25

As demonstrated in Table 4.1 direct control of the equivalence ratio can be achieved using methane. In Table 4.1 the flow conditions are the incoming streams at room temperature. the exit conditions are all at the exit temperature. In the last column, the residence time is determined by using the mass flow of the incoming streams and dividing it by the density of that material at the operating temperature to determine the volumetric flow rate. The reactor volume is then divided by the volumetric flow rate to determine the residence time of the gas mixture.

Once control of the equivalence ratio was established for methane, it needed to be established for a methane-biomass flow. As Table 4.2 demonstrates, the reactor was preheated by slowly increasing the methane flow form 410 cm^3/s to 900 cm^3/s while maintaining an air flow of 4955 cm^3/s. This was done to get the reactor up to operating

temperatures, as discussed in Chapter 2. At the methane flow rate of 900 cm^3/s, the flame appeared blue and wispy with the visible flame at the lid. The flame was relatively unstable so the methane flow was reduced to 780 cm^3/s, producing a ϕ of 1.5, coinciding with the critical smoke point of most hydrocarbon fuels. Once an equivalence ratio of 1.5 was reached, biomass was injected into the air stream until flame extinction.

During testing it was discovered that the air flows needed to inject and suspend biomass were lower (4955 cm^3/s) than those required in the gravity feed design. The amount of air required will depend on the type and size of biomass used. As table 4.2 shows, equivalence ratios from 1.74 to 2.40 were obtained, producing residence times of 15 seconds.

Table 4.2 Preliminary Run With Biomass

Flow Conditions				Exit Conditions			Stoichiometric Air Equivalence			
Q_{CH_4} $\left(\frac{cm^3}{s}\right)$	Q_{air} $\left(\frac{cm^3}{s}\right)$	$\dot{m}_{bio}$ $\left(\frac{g}{s}\right)$	ϕ	T_{exit} (K)	X_{CO_2}	X_{O_2}	CH_4 $\left(\frac{cm^3}{s}\right)$	Bio-mass $\left(\frac{cm^3}{s}\right)$	Total $\left(\frac{cm^3}{s}\right)$	t_r (s)
410	4955	0	.79	810	9.2	10.7	- -	- -	- -	19
570	4955	0	1.11	880	11.8	7.5	- -	- -	- -	17
780	4955	0	1.50	970	20.7	0.1	- -	- -	- -	16
900	4955	0	1.74	1060	- -	- -	- -	- -	- -	14
780	4955	.25	1.74	- -	- -	- -	7440	1210	8650	- -
780	4955	.57	2.06	- -	- -	- -	7440	2780	10200	- -
780	4955	.74	2.23	- -	- -	- -	7440	3620	11000	- -
780	4955	.91	2.39	- -	- -	- -	7440	4450	11900	- -

The equivalence ratio, in table 4.2, is based upon the stoichiometric air equivalence. For the given quantity of fuel, this is the amount of air needed for stoichiometric combustion.

$$Q_e = \frac{AFR Q_{CH_4} \rho_{CH_4}}{\rho_{air}}$$

Once this is determined for each fuel, they are then added together and the total divided by the air flow rate. The equivalence ratio is:

$$\phi = \frac{Q_{total}}{Q_{air}}$$

For the methane runs, the flame was again blue and wispy at the lid's surface with flames alternately exiting from different holes. For the biomass, the reactor gasses burned with an orange luminescence indicating the presence of soot within the exhaust gases. Again flames extended from the lid but were distributed evenly among the four exhaust ports. At the higher mass flow rates, biomass accumulated on the chamber's sides. The accumulated biomass consisted mostly of burnt particulate matter with a small unburned fraction. This produced a smoldering type fire on the chamber's side. The collection of biomass was attributed to the reduced air flow rates. Since not all of the biomass was pyrolized, the

actual equivalence ratio was lower than that predicted by flow measurements. Additionally this smoldering fire would contaminate the results because its local ϕ differs from that in the remainder of the chamber. Increasing the air flow to 6943 cm^3/s prevented this from occurring in all subsequent tests. Table 4.3 demonstrates that positive control of the equivalence ratio can be maintained.

Table 4.3 Final Biomass Verification

Flow Conditions				Exit Conditions			Stoichiometric Air Equivalence			
Q_{CH_4} $\left(\frac{cm^3}{s}\right)$	Q_{air} $\left(\frac{cm^3}{s}\right)$	$\dot{m}_{bio}$ $\left(\frac{g}{s}\right)$	ϕ	T_{exit} (K)	X_{CO_2}	X_{O_2}	CH_4 $\left(\frac{cm^3}{s}\right)$	Bio-mass $\left(\frac{cm^3}{s}\right)$	Total $\left(\frac{cm^3}{s}\right)$	t_r (s)
700	6943	0	.97	650	5.8	11.7	6700	- -	6700	17
820	6943	0	1.14	670	6.8	10.5	7800	- -	7800	16
1050	6943	0	1.47	820	8.7	6.8	10060	- -	10060	13
1230	6943	0	1.70	950	11.7	3.7	11740	- -	11740	11
1290	6943	.25	1.97	970	14.7	1.9	12300	1200	13500	11
1290	6943	.91	2.40	1030	15.9	1.4	12300	4450	16750	10

4.3 Discussion

In the previous chapter temperature data suggests that the mixing inside the chamber was complete as demonstrated by Fig. 3.1. However, examination of the data contained in Tables 4.1-4.3 suggests additionally that this mixing is incomplete from a combustion standpoint. Typically, as the equivalence ratio ϕ of a mixture approaches one the temperature increases to its maximum value near $\phi = 1$. Any further increase in the equivalence ratio produces a corresponding drop in the system temperature. Additionally, for $\phi > 1$ oxygen is completely consumed in the reaction. These patterns were not observed in this investigation. In reviewing the data in Tables 4.1-4.3, one observes that as the equivalence ratio increases the temperature continues to increase. In addition a large percentage of the product gasses consist of oxygen. These are both indications of incomplete mixing inside the reactor. One possible explanation is that although there is a recirculation of the reactants inside the chamber, there is a degree of incomplete mixing at the micro mixing level. As the methane flow was increased it was observed that temperatures increased inside the reactor. This may be a result of increases mixing caused by the kinetic effects of methane addition. As a result of this incomplete mixing, the equivalence ratio varies inside the chamber from fuel rich to fuel lean. This produces an inconsistency in evaluating the real equivalence ratio effects on soot production.

Improving the mixing could be accomplished in several ways. First the inlet hose could be reduced in diameter creating a jet nozzle effect. Second, the area between the flow director and the reactor could be decreased, producing the same effect. Third, baffle plates could be installed which increase mixing without impeding the biomass flow. Lastly, the reactor could be fitted with a hose that enters from the side with the same premixed equivalence ratio as is entering. This would create a cross flow and induce mixing.

The experimental runs were terminated when the chamber extinguished itself. This was primarily caused by a restriction of the air flow at the educator. Bridging of biomass at the eductor choked the air supply. If higher biomass flow rates are to be achieved then the educator needs to be enlarged from its present size.

In the current design, the flame is lit by a furnace starter attached to a long pole. This is acceptable for the present investigation but constitutes a hindrance for future experimentation in which the exhaust may be ported a secondary chamber for completion of combustion under fuel-lean conditions. Initially the ignition wire was run inside the burner supports, but at operating temperatures the wire began to burn causing perturbations in the data. Overcoming this problem necessitates reworking the ignition system.

Bibliography

Adams, T.N. "A Simple Fuel Bed Model for Predicting Particulate Emmissions From a Wood Waste Boiler," *Combustion and Flame*. 39 number 3 1980: 225-239.

Becker, H.A., and Liang, D. "Total Emission of Soot and Thermal Radiation by Free Turbulent Diffusion Flames," *Combustion and Flame*. 44 number 1-3 1982: 305-318.

Bertrand, C. and Delfau, J.-L. "Mechanism of Soot Formation in Hydrocarbon Flames," *Combustion Science and Technology*. 44 1985: 29-45.

Bilger, R.W. "Reaction Rates in Diffusion Flames," *Combustion and Flame*. 30 1977: 277-284.

Brown, N.J.; Dod, R.L.; Mowrer, F.W.; Navakov, T.; and Williamson, R.B. "Smoke Emission Factors from Medium Scale Fires: Part 2," *Aerosol Science and Technology*. 10 number 1 1989: 20-28.

Bush, B.W., and Small, R.D. *Smoke Produced by Nonurban Target-Area Fires Following a Nuclear Exchange*. Los Angeles:: Pacific-Sierra Research Corporation [1985].

Calcote, H.G. "Mechanisms of Soot Nucleation in Flames - A Critical Review," *Combustion and Flame*. 42 number 3 1981: 215-242.

Chapman, A.J. *Fundamentals of Heat Transfer*. New York: Macmillan Publishing Company, 1987.

Chen, Y.; Fiend, A.; Tewari, S.S.; and Sibulkiw, M. "Combustion of Pure and Fire Retardant Cellulose," *Combustion and Flame*. 84 number 1-2 1991: 121-140.

Chippet, S., and Gray, W.A. "The Size and Optical Properties of Soot Particles," *Combustion and Flame*. 31 number 2 1978:

Crutzen, P., and Andreae, M.O. "Biomass Burning in the Tropic: Impact on Atmospheric Chemistry and Biogeochemical Cycles," *Science*. 250 (21 December 1990): 1669-1678.

Dixon-Lewis, G.; Bradley, D.; and Habik, S. "Oxidation Rates of Carbon Particles in Methane-Air Flames," *Combustion and Flame*. 86 1991: 12-20.

*Press, F. (Chairman, NRC) *The Effects on the Atmosphere of a Major Nuclear Exchange*. Washington DC: National Academy Press, 1985.

Fleagle, R.G., and Businger, J.A. *An Introduction to Atmospheric Physics.* New York: Academic Press Inc, 1980.

Glassman, I. *Combustion.* Orlando: Academic Press Inc, 1987.

Goldberg, Edward D. *Balck Carbon In The Environment.* New York: John Wiley and Sons, 1985.

Goldhammer, J.G., gen. ed. *Ecological Studies* 84 vols. Berlin: Springer-Verlag., 1990. Vol 84: *Fire in the Tropical Biota*, By D. E. Ward.

Goody, R. M., and Yung, Y.L. *Atmospheric Radiation Theoretical Basis.* New York: Oxford University Press, 1989.

Haynes, B. S., and Wagner, H. G., "Soot Formation" *Progress in Energy and Combustion Science.* 7 1981: 229-273.

Heywood, John B., *Internal Combustion Engine Fundamentals.* New York: McGraw-Hill Book Company, 1988.

Holman, J. P., *Heat Transfer*, Fifth Edition New York: McGraw Hill Book Company, 1981.

Homan, Howard S. "The Dependence of Soot Yield on Flame Conditions-A Unifying Picture" *Combustion Science and Technology.* 33 number 1-4 1983: 1-16.

Howard, Jack B. "On the Mechanism of Carbon Formation in Flames" *Twelveth Symposium (International) on Combustion.* 877-887, The Combustion Institute, 1969.

van de Hulst, H. C., *Light Scattering by Small particles.* New York: Dover Publications Inc., 1981.

Kennedy, Ian M.; Kollmann, Wolfgang: and Chen J.-Y., "A Model for Soot Formation in a Laminar diffusion Flame" *Combustion and Flame.* 81 1990: 73-85.

Kent, J. H., and Wagner, H. G. "Why Do Diffusion Flames Emit Smoke?" *Combustion Science and Technology.* 41 1984: 245-269.

Kyle, Thomas G. *Atmospheric Transmission Emission and Scattering.* New York: Pergamon Press, 1991.

La Nauze R. D. "A review of the fluidized bed combustion of biomass" *Journal of the Institute of Energy*, 66-76, June 1987.

Lefebvre, A. H. "Pollution Control in Continuous Combustion Engines" *Fifteenth Symmposium (International) on Combustion.* 1169-1180, The Combustion Institute, 1975.

Kee, Robert S. *Progress Report Combustion Gas Synthesis* 17 June 1989.

Markstein, G. H. *Soot Formation, Radiant Emission and Absorption in Laminar Ethylene and Propylene Diffusion Flames.* Norwood Massachusetts: Factory Mutual Research, [1983].

Martin, Stanley "Diffusion-Controlled Ignition of Cellulosic Materials by Intense Radiant Energy" *Tenth Symposium (International) on Combustion.* 977-896, The Combustion Institute, 1965.

Monastersky, R. "A smoke screen for greenhouse warming?" *Science News* 141.number 21 1992: 343.

Narcsimhan,K.S., and Foster, P.J. "The Rate of Growth of Soot in Turbulent Flow with Combustion Products and Methane" *Tenth Symposium (International) on Combustion.* 253-257, The Combustion Institute, 1965.

Peterson, Janice I "Development of a PM-10 Emissions Inventory from Prescribed Fire in the United States During 1989" Paper presented at the 84th Annual Meeting and Exhibition of the Air and Waste Management Association 21 June 1991.

Radke, L. F., and Ward, D. E. "Prescriptions for Biomass Fire Smoke Reductions."

Radke,L. F.; Lyons, J. H.; Hobbs, P. V.; Hegg, D. A.; Sandberg, D.V.; and Ward, D. E. A *Final Report on the Airborne Monitoring and Smoke Characterization of Prescribed Fires on Forest Lands in Western Washington and Oregon.* Las Vegas" Environmental Monitoring Systems Laboratory, {1985}.

Robock, Alan "Enhancement of Surface Cooling due to Forest Fire Smoke." Science. 242 (11 November 1988): 911-913.

Sawyer, Robert F. "The Formation and Destruction of Pollutants in Combustion Processes: Clearing the Air On The Role of Combustion Research" *Eighteenth Symposium (International) on Combustion.* 1-22 The Combustion Institute.

Sivathanu, Y. R., and Faeth, G. M. "Soot Volume Fractions in the Overfire Region of Turbulent Diffusion Flames: *Combustion and Flame.* 81 1990: 133-149.

Sivathanu, Y. R., and Faeth, G. M. "Temperatures/Soot Volume Fraction Correlations in the Fuel-Rich Region of Buoyant Turbulent Diffusion Flames" *Combustion and Flame.* 81 1990: 150-165.

Steffensen, R. J.; Agnew, J. T.; and Olsen, R. A. *Combustion of Hydrocarbons-Property Tables.* Lafayette: Purdue University, 1966.

Then, C. L., and Lee, S. C. "Flame Radiation" *Progress in Energy and Combustion.Science.* 8 1982: 41-59.

Turco, R. P., and Golitsyn, G. S. "Global Effects of Nuclear War" *Environment.* 30 number 5 1988: 8-15.

Udlock, D. E.; McKay, R.A.; and Vettar, A. A. "An Effective Combustion Enhancer for Chapparral Removal" *Combustion Science and Technology.* 17 number 1-2 1977: 79-82.

Vaughn, Craig B.; Sun, William H.; Howard, Jack B.; and Longwell, John P. "Measurements and Modeling of Light Hydrocarbons in Rich C2H4 Combustion in a Jet Stirred Reactor" *Combustion and Flame.* 84 1991: 38-46.

Ward, D. E.; Babbitt, R. E.; Susott, R. A.; Blakely, A. D.; and Hao, W. M. "Field Characterization of Smoke Emissions from Biomass Fires Using Computer-Controlled Measurement Techniques."

Ward, Darold E., and Hao, Wei Min "Projections of Emissions From Burning of Biomass For Use in Studies of Global Climate and Atmospheric Chemistry."

Ward, Darold E., and Hardy, Colin C. "Smoke Emissions From Wildland Fires." *Environment International.* 17 1991: 117-134.

Ward, Darold E.; McMahon, Charles K.; and Johanson, Ragnar W. "An Update on Particulate Emissions from Forest Fires." Paper presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, Oregon 1 July 1976.

Weatherford, W. d., Jr., and Sheppard, D. M. "Basic Studies of the Mechanism of Ignition of Celulosic Materials" *Tenth Symposium (International) on Combustion.* 897-910, The Combustion Institute, 1965.

Weinberg, Felix., ed, *Advanced Combustion Methods.* New York: Academic Press, 1986.

Weisborg, B. L.; Yeung, A. C.; and Howard, J. B. "Concentration and Mass Distribution of Charged Species in Sooting Flames" *Fifteenth Symposium (International) on Combustion.* 1439-1448, The Combustion Institute, 1975.

Wright, F. J. "The Formation of Carbon Under Well Stirred Conditions" *Twelveth Symposium (International) on Combustion.* 867-875, The Combustion Institute, 1969.

Wright, F. J. "The Oxidation of Soot by O Atoms" *Fifteenth Symposium (International) on Combustion.* 1449-1460, The Combustion Institute, 1975.

Appendix A

Calibration Data

A1 Cole Parmer FM 044-40ST

Float Material	316 Stainless Steel Ball
Float Density	8.04 g/ml
Metering Temperature	70 F
Metering Pressure	14.70 PSIA
Metering Density	0.0006653 g/ml
Metering Viscosity	0.01099 Centipoise

A2 Flow Rates

Scale Readings	Flow (ml/min)
150	59144.4
140	54449.6
130	50000.0
120	45744.9
110	41365.9
100	37019.8
90	32844.2
80	28601.7
70	24391.3
60	20487.7
50	16706.8
40	13048.5
30	9550.6
20	6159.5
10	2942.8

Appendix B

Heat Transfer Calculation

B.1 Introduction

As discussed in Chapter 3, during the course of this investigation, measured and predicted temperatures did not coincide. In order to account for these differences, a heat balance was conducted to determine the heat loss. This appendix discusses the general method used to determine the heat loss. It begins with the calculation of the free stream velocity, which is needed to determine the Reynolds number for the next two sections. The Appendix continues with a discussion of the heat loss from both the lid and the chamber walls. The final section discusses the methods used to determine the heat generated from methane combustion.

B.2 Free Stream Velocity

In order to simplify the heat transfer calculations, the problem was reduced to a one dimensional estimation. This was accomplished by opening the chamber and treating it as a flat plate. Although this provides only an approximate solution, the objective of this analysis was twofold. First, to determine where the majority of the heat loss was occurring. Second, to ensure that the entire system was in heat balance. In order to determine the heat transferred to the surrounding area, the free stream velocity must be calculated to determine if turbulent or laminar flow exists. This will determine the relations needed in the calculation of the heat transfer. Looking at figure B.1 and using conservation of mass

$$\dot{m}_{in} = \dot{m}_{out}$$

so

$$\dot{m}_{out} = Q_{in}\,\rho_{in}.$$

In addition, there are no temperature nor pressure changes from point A to B therefore:

$$\rho_{in} = \rho_{out}$$
$$Q_{in} = Q_{out}$$

where

$$Q_{out} = A_{out} u_{\infty}.$$

A_{out} is defined as the conical area formed between the diffuser and chamber sides (lines c-d). The free stream velocity is:

$$u_\infty = \frac{\dot{m}}{\rho A_{out}} = \frac{Q}{A_{out}} = Q(17.11)\ \frac{m}{min}$$

where Q is the value read from the flowmeter in SCFM. Substituting the measured flow rate into this equation produces a velocity of 5.8m/s. The Reynolds number is then defined by a position x along the plate and is written:

$$Re_x = \frac{u_\infty x}{v}$$

Using the interior chamber temperature of 1040 K the fluid properties are:

PR = 0.702
k = 67.54 x 10^{-3} w/m K
v = 115.61 x 10^{-6} m^2/s
x = 1.06 m

The calculated Reynolds number is 5.4 x 10^4. Therefore, the flow remains laminar over the length of the plate.

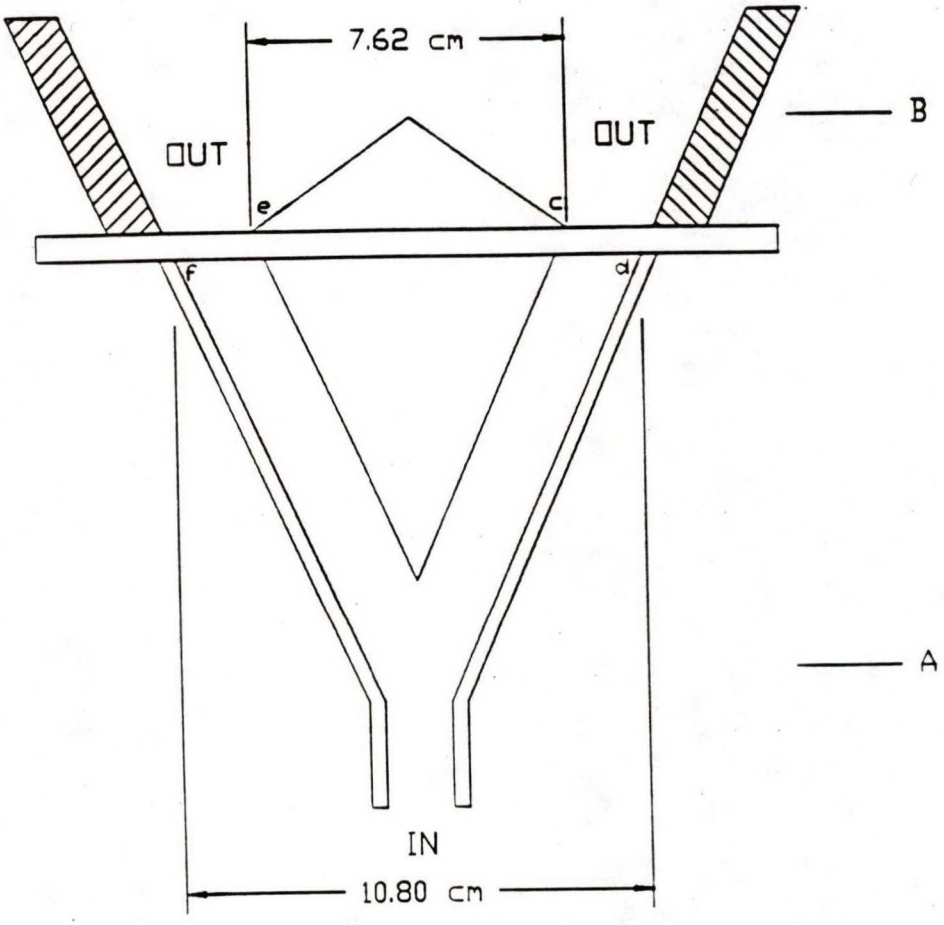

Figure B.1 Flow Director

B.3 Wall Calculations

The simplest way to determine the heat transfer is to model the system as a circuit network. As discussed on Chapter 1, the chamber was designed to remove any dependence on free convection in the interior. Therefore, the primary methods of heat transfer are forced convection and conduction. The total heat transferred through the wall is represented by (Chapman 1984):

$$q = \frac{t_1 - t_2}{R_c + R_k} \qquad \text{(B - 1)}$$

The temperatures were determined experimentally as discussed in Chapter 3, but the resistances were determined analytically.

The convective resistance is defined as (Chapman 1984):

$$R_c = \frac{1}{h_x A}$$

where h_x is the local heat transfer coefficient along the plate. For laminar flow past a flat plate, Chapman (1984) defines the heat transfer coefficient as:

$$h_x = \frac{k}{x}(0.332)Pr^{\frac{1}{3}}Re_x^{\frac{1}{3}} \qquad \text{(B - 2)}$$

Based on the local Nusselt number. Integrating this expression over the length of the plate:

$$h_L A = \int_0^L h_x dA$$

determines the convective resistance. Substituting the values listed in the previous section:

$$h_L A = 12.4 \frac{W}{K}$$

$$R_c = 8.14 \times 10^{-2} \frac{K}{W}$$

The conductive resistance for B-1 is defined as:

$$R_k = \frac{\Delta x}{kA} \qquad \text{(B - 3)}$$

where k is the thermal conductivity and Δx is the wall thickness. In this analysis the resistance of the steel to heat transfer is negligible compared to the Kaowool insulation. In order to calculate the conductive resistance of the Kaowool, the thermal conductivity must first be determined. The thermal conductivity, from the Kaowool catalogue, is a function of temperature and is approximated by the linear relation:

$$k = (1.75 \times 10^{-4})\ T - 0.036 \qquad (B - 4)$$

where T is in °C. Therefore:

$k = 0.98$ W/m°C

$A = 1.63$ m^2

$\Delta x = 0.0254$ m

and

$R_k = 0.158$

Substituting these resistances in B

$q = 3.1$kW

produces an approximate heat transfer throughout the chamber's sides.

B.4 Lid Calculations

In calculating the heat transfer from the lid, extensive approximations were used for ease of calculations. Using the same circuit analogy, the resistances that had to be determined at the lid were forced convection in the interior, free convection and radiation form the exterior. The air flow at the lid's interior was extremely complex due to the mixing associated with combustion. Determination of a Reynolds number was impossible, therefore to simplify the calculations it was assumed that the airflow at the lid was laminar. Then the lid was sectioned into pie pieces and equation B-2 was used to determine the heat transfer coefficient. The equation for the heat transfer is

$$q = \frac{t_{inside} - t_{ambient}}{R_k + R_c + R_e} \qquad (B - 5)$$

where

$$R_e = \frac{R_{free}\, R_{rad}}{R_{free} + R_{rad}} \qquad (B - 6)$$

For this analysis, the conductive resistance of the steel was negligible, therefore $R_k=0$. For the case of an insulated surface, using Kaowool, R_k is calculated by B-3 with k determined from B-4.

The next step was to determine R_{free}. In order to do this, the lid was modeled as a flat plate with the heated surface facing up. The heat transfer coefficient (Chapman 1984) for free convection is determined from:

$$Nu = CRa_L^m$$

where the values of m and C depend on the Rayleigh number. The Rayleigh number is defined as:

$$GrPr \qquad \text{(B - 7)}$$

and the Grashoff number

$$Gr = \frac{g\beta(t_1 - t_\infty)L^3}{\upsilon^2}. \qquad \text{(B - 8)}$$

All of the parameters, discussed above, are based on a characteristic length defined by Chapman (1984) as:

$$L = \frac{\text{plate area}}{\text{plate perimeter}}.$$

Based on this value and the fluid properties

$L = 0.28$ m
$\beta = 3.35 \times 10^{-3}/K$
$\Delta t = 741.85$ K
$g = 9.8$ m/s^2

the Grashoff number is 4.0×10^7. This corresponds to a Tayleigh number of 2.8×10^7. The value of C is 0.15 and the value of m is 1/3 (Chapman 1984). The heat transfer coefficient is then:

$$h = \frac{k}{L} C Ra_L^m$$

and the free convective resistance is :

$$h = 11 \frac{W}{m^2 °C}$$

the next step was to calculate the radiation resistance term in the heat transfer equation. From the net energy exchange for radiation

$$q = \sigma A \varepsilon (T_{inside}^4 - T_{ambient}^4) = \frac{T_{inside}^4 - T_{ambient}^4}{R_{rad}}$$

Therefore:

$$R_{rad} = \frac{1}{\sigma A \varepsilon (T_{inside}^2 + T_{ambient}^2)\,(T_{inside} + T_{ambient})}. \qquad \text{(B - 9)}$$

Where $\sigma = 5.669 \times 10^{-8}$ W/m^{2}K^4. An $\varepsilon = 0.9$ was chosen for steel. Substituting these values in B-9 the resistance becomes

$$R_{rad} = 0.012 \frac{°C}{W}$$

Using B-6 the equivalent resistance is

$$R_e = 1.06 \times 10^{-2} \frac{°C}{W}$$

Using B-2 the convective resistance is

$$R_c = 9.57 \times 10^{-2} \frac{°C}{W}$$

Substituting these values into equation B-5 the heat transferred through the lid is

$$q = 6.9kW$$

B.5 Thermodynamic Calculations

The next step was to determine the heat transferred tot he incoming air. A simple thermodynamic analysis yields.

$$q = \dot{m}(h_{out} - h_{in})$$

where h is the enthalpy of the gas stream. The mass flow of air is 0.012 kg/s and the temperature of the reactor is 1040 K. Therefore

$$q = 0.01(1091.85 - 300.19)\ kW$$
$$q = 7.9\ kW$$

B.6 Combustion Calculations

The last step in this analysis is to determine the heat generated by combustion for comparison with that radiated to the environment by the chamber. The heat evolved by the combustion of methane is given by the relation (Glassman 1987):

$$q = \sum_P^P \eta_i [H_{f_{298}} + \Delta H_{sens}] - \sum_R^R \eta_i [H_{f_{298}} + \Delta H_{sens}].$$

The enthalpy of formation and the sensible enthalpy were determined by estimating the products of combustion. It was assumed that since this is a fuel lean mixture, that all of the hydrogen is oxidized giving the formulation:

$$\phi CH_4 + 2[O_2 + 3.76N_2] \leftrightarrow 2H_2O + xCO_2 + yCO + zO_2 + 7.52N_2$$

Then based on the exact equivalence ratio, ϕ =1 for this analysis, and the mole fraction of oxygen (0.083) and carbon dioxide (0.091) this equation becomes:

$$CH_4 + 2[O_2 + 3.76N_2] \leftrightarrow 2H_2O + 0.96CO_2 + 0.04CO + 0.02O_2 + 7.52N_2$$

Substituting these values in B-10 and using the JANAF Tables in Glassman (1987)

$$q = 17.4 \text{ kW}$$

There is then a 0.5 kW difference between what is being produced by combustion and that being transferred to the working fluid and that which is lost to the environment. This difference can be attributed to the one dimensional approximation that was made at the outset.

Appendix C

Experimental Procedures

C.1 Introduction

This appendix discusses the standardized procedures for operating the chamber. These were developed during the fabrication phase of this investigation. The operation of the chamber requires a minimum of two people. One to record data and the other to operate the biomass feed system.

C.2 Test Procedures

1) Verify operability of thermocouples
2) Place two thermocouples in the exhaust at lid level
3) Ensure cold trap set up
4) Insert analyzer probe at lid level
5) Turn on analyzers an pump
6) Verify analyzer is operating properly
7) Shut off methane valve to chamber
8) Shut off regulator valve
9) Verify transformer is operational
10) Open methane cylinder
11) Open methane regulator valve to a pressure of 20 psig
12) Establish air flow
13) Open methane valve to chamber
14) Ignite methane
15) Increase methane flow to desired f slowly
16) Allow system to stabilize
17) Record pressure at flow meters - air, methane
18) Record flow at flow meters - air, methane
19) Record temperatures
20) Record mole fractions of O_2 and CO_2
21) Turn vibrator on
22) Turn auger on to the desired control setting 1-10
23) Record controller setting
24) Record temperatures
25) Record mole fractions of O_2 and CO_2

Part II

COMMENTS AND RECOMMENDATIONS

by

Richard C. Corlett
Principal Investigator

1. The Design Concept Adopted for this Program

The design concept was adopted early in this program. In effect, it called for a stirred reactor with particulate solid fuel and air, possibly vitiated, as reactants. Moreover, in order to achieve the desired residence time on the order of 10 to 20 seconds, a reactor with characteristic length of order of 1 meter was required.

This concept was driven by the sponsor's desire for a convenient experiment which would exhibit effects on pollutant formation ascribable to fuel chemistry, moisture and, perhaps, microstructure without the complication of fuel-bed geometry variation. Pulverized fuel entrained in gases was, in a sense, to constitute a standardized fuel-bed. Also, the system would, at least in principle, be operable in a steady mode which would provide some advantage in measurement and sampling.

1.1 Residual and non-residual particles

Particulate matter in fires can be classified as residual and non-residual. By residual matter is meant the incompletely gasified remains, often mainly char, of the original solid fuel. In the present gasifier concept wherein the fuel is supplied exclusively in the form of pulverized, all residual matter must necessarily appear as particulate in the exit stream.

Particulate matter which is created from gas molecules via nucleation and growth in the gas phase is denoted as non-residual. A main purpose of this program was to test the hypothesis that non-residual particulate is importantly effected by fuel-rich residence time. To the extent that significant residual particulate matter was produced, distinguishing residual from non-residual particulate would be a critical aspect of data interpretation.

An inherent feature of this concept is that, while the gas-phase residence time could be controlled over a wide range by reactor design, the solid-to-gas pyrolysis characteristic time would necessarily be very short - on the order of 1 second for 1 millimeter particles and varying proportional to the square of the particle length dimension. This would appear to restrict pyrolysis to low-char-yield pathways. Low-char-yield in itself would tend to reduce production of residual particulate matter. Also, low-char-yield pathways tend to yield gases rich in combustible C-H-O fragments, as opposed to H_2O and CO_2 . Such combustible fragments also tend to produce carbonaceous smoke.

The above points notwithstanding, it is impossible to predict from first principles and/or existing data correlations the qualitative characteristics of residual particulate that might be produced in this reactor. Indeed the envelope of conditions for any production of residual particulate cannot be predicted. Two possibilities which could greatly complicate interpretation of experimental data come readily to mind. One is that, by virtue of the low-char-yield pathway, the residual char particles would lack physical integrity and, hence, disintegrate to particles much finer than the original fuel particles. The resulting fine particles might be indistinguishable from non-residual particles. The other is that residual particles would retain physical integrity and, during the residence time of interest, would attach matter from the fuel-rich gases or conglomerate with much finer non-residual particles to form a sort of hybrid particles.

These complications would be worth studying if realistic. However, it is unlikely that wildland fuels would offer the same potential for formation of residual particulate matter as would a burner with entrained pulverized fuel. Even wildland fuels classified as "fine" are much courser from an entrainment standpoint from an entrainment standpoint than pulverized fuel. Under circumstances conducive of large sustained volumes still courser fuels would come into play. Thus, in retrospect, there exist serious concerns about the entrained pulverized fuel concept.

1.2 Engineering problems

Making a reactor on the 1 meter scale introduced a number of difficult engineering problems. In order to produce a workable flow geometry at affordable cost, a steel containment was necessary. Considerable care and engineering compromise was needed to avoid overheating. Even so, the flow geometry was far from ideal for a stirred-reactor, which led to much loss of time dealing with combustion stability phenomena.

2. Alternative concepts

2.1 Principal Investigator's original concept

The original concept that the Principal Investigator had in mind was a fixed bed, perhaps a crib, in a brick-insulated box with air flow controlled to achieve a desired equivalence ratio in terms of the oxygen requirement of the gasifying solid fuel. Monitoring this oxygen requirement would have required extra work but would have been well within the capability of the Principal Investigator's laboratory. A simple load cell, corrected for buoyant flow forces, could have tracked the mass gasification. An ultimate (as opposed to actual) oxygen consumption calorimetry technique developed under separate contract to the Naval Surface Warfare Center could have been used to determine the oxygen requirement per mass gasified fuel. Varying crib size, fuel element fineness, and packing ratio would have been feasible with standardized woods and, with some experimentation, could have provided a useful range of air volume flows for prescribed equivalence ratios. With a selected air flow, the residence time could have been varied by varying the volume of the container. It would not have been prohibitively expensive to make several chambers of different volumes. Another possibility would have been to arbitrarily reduce the volume of a single chamber by adding layers of firebrick.

The above approach does not offer an immediate route to working with fuels too fine to be assembled into standardized and reproducible fuelbeds. However, it is the judgment of the Principal Investigator that any approach to studying smoke from very fine fuels will be beset with serious difficulties of operation or data interpretation or both. On the other hand, the basic hypotheses to be tested, e.g., that non-residual particulate amount

and qualities depend on fuel-rich residence time, do not appear to have any intrinsic link to fuel fineness *per se*. The logical approach would therefore appear to be to first test hypotheses and explore phenomena in regimes where experimental difficulties are least, i.e., with feasible standardized wood assemblies, and to worry later about problems with fine fuels.

It is acknowledged that the "fire in a box" approach outlined above is somewhat inelegant. The attainable degree of equivalence ratio and residence time precision would probably not be very high. There would be some problems with gas-phase uniformity, wall accumulation of particulate matter, and the like. This would have been compensated by the fact that the basic phenomena of interest could have been attained relatively quickly and cheaply. The essence of the answers sought might have been obtained on the basis of approximate data before investing much time and energy to refine combustion control.

2.2 Other alternatives

Other alternatives that come to mind are:

- **Stay with the entrained particulate reactor but abandon the long residence-time feature.** This would allow working with a bench-scale reactor which would be much less expensive to build and operate and would be more flexible. Study the production of residual particulate which, presumably, is independent of residence time, possibly identifying regimes free of the residual/non-residual discrimination problem indicated above. It might be possible to combine a centrifuge with the basic reactor eliminate residual particles. Better yet would be to gain enough understanding of the effect of residual particles on observed non-residual matter to support interpretation of larger, long residence time experiments.

Develop an independent oxygen-free gasifier. It appears feasible to develop a gasifier wherein hot neutral gas (nitrogen) would be forced through a bed of fuel ground to a calculated surface to volume ratio but protected from gas entrainment by screens. The gasified fuel could then be brought to reactive conditions by admixture with hot combustion products. The mixing process, being purely gas-phase, could be accomplished quickly. The resulting homogeneous mixture could then be "matured" under near-stagnant conditions in an insulated chamber. Low velocities would be permissible so that a wide range of residence times might be achieved with a modestly sized chamber. This sounds too good to be true and, to some extent, it is. The design of the gasifier probably would require as much engineering trouble-shooting as the original long residence time gas generator problem.

2.3 Reminder

It is important to recall that the objective of the research is understanding of emission factors from large wildland fires as a function of pertinent variables. The latter include fire physical variables as well as fuel type. Because we cannot get the desired information from straightforward full-scale tests we need some rational understanding of the processes in order to interpret whatever scale and diversity of testing that we can afford. At this stage of our understanding, job one is to identify the most important variables and gain "first order" knowledge of how smoke properties depend on them.

3. Recommendations

The goal of a standardized test apparatus that would work with arbitrary bio-fuels and encompass the range of physical combustion variables attempted was over ambitious. The gas generator work to date should be abandoned for the time being.

3.1 Objectives

Research to elucidate the effects of physical combustion variables or those of fuel chemistry and micro-structure, i.e., fuel identity, on smoke properties should be addressed separately. If resources to do both are not available, a prioritization decision needs to be made. Additionally, realistic data targets should be set. What variable need to be explored and to what degree of precision. The writer would support crude, highly approximate attacks on both types of effects before designing sophisticated experiments which are likely to be unpredictably expensive and lengthy.

3.2 Fire in a box with fuel cribs

Pending refinement of objectives by the USDA Forest Service, the Principal Investigator recommends that, if further work is to be done in this field, simple but carefully planned experiments of the type described in Section 2.1, above, be carried out. The fuel should be wood cribs, with chemistry effects exhibited by choice of as widely variable wood chemistry as achievable with existing species. A standard overall crib size should be selected and an array of crib variables specified. Two "boxes" should be constructed, with the smaller sized to contain without excessive interference the fastest burning crib arrangement. (It is noted that fuel-rich burning is of primary interest). The second box should have 10 times the volume of the first.

Phase I would consist of enough experimentation to reveal the gasification rates for all crib arrangements and fuel identities selected for study. Recognizing that these gasification rates for cribs will probably not be constant over time, suitable averages for periods of perhaps 100 seconds should be identified.

Phase II would consist of development of means to characterize the effluent from the fuel-rich box for a time corresponding to a selected gasification rate and air supply to a selected equivalence ratio. Diagnostic output would include opacity at one or more wavelengths, particulate mass fraction before and after sample carbonization, and a measure of particle size. Probably some gas analysis should be done. Beyond CO and CO_2 and trapping of H_2O, meaningful gas analysis becomes complicated and expensive. Carefule planning based on reasonably clear information needs would be in order before undertaking gas analysis beyond major species. Some idea of the influence of residence time, equivalence ratio, crib structure and wood chemistry on such outputs as are measurable per above should be in hand before a decision to go ahead with Phase III and associated detailed planning.

Phase III would consist of downstream, more or less fuel-lean, burning of effluent from the fuel-rich box. The simplest approach would be diffusive burning in ambient air. However, this would not provide much flexibility of fuel-lean residence time.

4. A far-out suggestion

In recent experiments in our Pressurable Fire Chamber (PFC) we have found that increasing pressure sharply increases smoke yield. A tempting conjecture is that the

increased pressure accelerates the same processes as occur in larger standard atmosphere fires. If so, pressurization might, in some sense not yet quantified, be equivalent to increasing residence time. At the present time we do not have in place the diagnostic tools to evaluate the degree to which such equivalence would be valid.

5. Concluding remarks

A main thrust of the foregoing discussion is that the gas generator project, as pursued with partial USDA Forest Service support over the last four years, was flawed and that the Principal Investigator's original concept should have been pursued instead. The USDA Forest Service is not in any way "to blame" for this situation. Although the change of concept was meant to better serve the sponsor's interests as he understood them after late 1988 meetings with USDA Forest Service personnel, **the Principal Investigator is solely responsible for the choice of course that was adopted**. Indeed, the conical, entrained fuel stirred reactor concept was developed by the Principal Investigator on his own.

It is probably true that, with more productive student effort and better luck, the project would have gotten further. However, the intrinsic difficulties - residual versus non-residual particulate, combustion instability, etc. - outlined above would inevitably have made difficult the acquisition of decisive data.

Finally, the recommendations above should not be construed as proposals by the Principal Investigator on his own behalf as a University of Washington professor. He will probably retire after a couple of more years and has no intention to initiate and be responsible for new experimental projects. Even the PFC, used for more than a decade for the Principal Investigator's research supported by the U.S. Navy, has now been shipped back to the Naval Surface Warfare Center in Maryland. The Principal Investigator would be pleased to consult with the USDA Forest Service, even if only informally, if it chooses to pursue any of the recommendations set forth above.